STUDY OF IN-MEDIUM MESON MODIFICATION IN 12 GeV p + A REACTIONS

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** Presented at MESON 2006, Cracow, Poland, June 2006*

Abstract

Invariant mass spectra of low-mass vector mesons in the e^+e^- channel are measured in 12 GeV p + C and p + Cu reactions ($\sqrt{s}$ = 5.1 GeV) at the KEK Proton Synchrotron. A significant excess is observed on the low-mass side of the ω meson peak over the known hadronic sources in the data of both C and Cu targets. Further, below the ϕ meson peak, an excess is found in the Cu target data for slowly moving mesons whose $\beta\gamma$ value is less than 1.25. They can be interpreted as signatures of the spectral modification of vector mesons in cold nuclear matter.

1 Introduction

In modern hadronic physics, it is understood that the origin of hadron mass, which is determined primarily by the effective mass of constituent quarks, is due to the spontaneous breaking of the chiral symmetry. Since the restoration of such broken symmetry is expected in hot and/or dense matter, many theoretical studies have been conducted on the hadron spectral modification in medium. In particular, for dense cold matter, the in-medium scaling law was proposed by Brown and Rho[1], which predicts approximately 20% of hadron mass reduction at the normal nuclear density ρ_0. Based on the QCD sum rule, Hatsuda and Lee predicted the vector meson mass reduction that scales to the nuclear density ρ in the range from 0 to $2\rho_0$. According to their prediction, the expected mass reduction at ρ_0 is 16 ± 6% for ρ and ω mesons and approximately 1∼4% for the ϕ meson[2].

Several experiments that aim to observe such a hadron modification have been performed. Using high-energy heavy ion beams, CERES[3] and NA60[4] at the CERN SPS reported ρ meson spectral modifications in the e^+e^- and $\mu^+\mu^-$ channels respectively, however, they did not observed any modification in proton-induced reactions. At lower incident energies, CBELSA/TAPS reported an ω meson modification in the $\pi^0\gamma$ decay channel in a few GeV γ + A reactions[5]. CLAS G7[6] and HADES[7] measured ρ, ω, and ϕ in the e^+e^- channel in photon and heavy-ion induced reactions. In 12 GeV p + A reactions, the present experiment KEK–PS E325 reported modifications of ρ and ω mesons[8] [9] and the ϕ meson[10] in the e^+e^- channels, as described below.

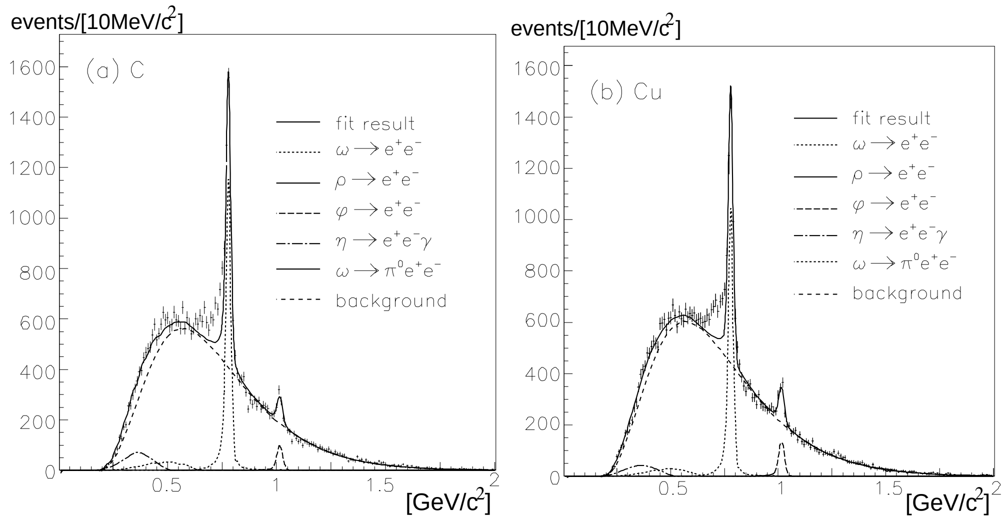

Figure 1: Inclusive e^+e^- invariant mass spectra. The spectrum for the C target is shown on the left panel while that for the Cu target is shown on the right panel. For each target, a significant excess over the fit result is observed on the left side of the ω peak. The best fit provides zero amplitudes of the ρ meson .

2 Experiment

We performed the experiment E325 at the KEK 12 GeV Proton Synchrotron. This experiment was proposed in 1993; detector R & D began in 1994 and the spectrometer construction began in 1996. Physics runs began in 1997 and continued until 2002 along with some simultaneous detector upgrades. The first e^+e^- results from the data taken in 1998 are reported in Ref. [8]. In the present manuscript, we describe the recent results[9] [10] [11] [12] obtained by using the data taken in 2001 and 2002, which are the last two data-taking periods.

The magnetic spectrometer was designed to detect e^+e^- pairs and K^+K^- pairs from vector-meson decays; it was located at the KEK–PS EP1–B primary beam line. A 12 GeV primary proton beam was used to produce the vector mesons as ρ, ω and ϕ using carbon (C), copper (Cu), polyethylene, and lead as the nuclear targets. Most of the statistics were accumulated using C and Cu targets. Detailed descriptions of the spectrometer are provided in Ref. [13].

The detector simulation code was developed using the GEANT4 toolkit[14] to evaluate the experimental effects on the mass spectra: the Bethe-Bloch type energy loss, which shifts the peak position to a lower side; Coulomb multiple scattering, which broadens the peak width; and bremsstrahlung, which produces a long tail on the low-mass side of the resonance peak. Detector efficiencies, tracking efficiencies and geometrical acceptances are also included in the simulation. We obtained a mass resolution of 10.7 MeV/c^2 for the ϕ meson in the e^+e^- channel. The observed peak shape of $\phi \to e^+e^-$ as well as the peaks of $K^0_s \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ [10] [13]. were well reproduced by the simulator.

3 Analysis of $\rho/\omega \to e^+e^-$ spectra

The inclusive e^+e^- invariant mass spectra for the C and Cu targets are shown in Fig. 1 with a best-fit decomposition into the known hadronic sources as $\phi \to e^+e^-$, $\rho \to e^+e^-$, $\omega \to e^+e^-$, $\omega \to \pi^0 e^+e^-$ and $\eta \to \gamma e^+e^-$, and the combinatorial background, which was estimated by the event mixing method, as described in Appendix A[9].

To obtain the resonance shapes, the relativistic Breit-Wigner formula (2), which is explained in Appendix B, was used. Kinematical distributions of the mesons were given by the inter-nuclear cascade code JAM[16], which reproduces the observed kinematical distributions of ω and ϕ mesons[11]. The generated mesons were decayed to e^+e^- , filtered through the detector simulation described in the previous section to take experimental effects into account, and used to fit the data with the mixed-event background. Relative abundances of the mesons and the background were determined by the fit.

For both the C and Cu targets, a significant excess was found on the low-mass side of the ω meson peak. When the excess region 0.60$\sim$0.76 GeV/c^2 was excluded, the observed data were well reproduced by the fit; however, the fit failed when this region was included. In the former case, the yield of excess was integrated in the region and the statistical significances of the excess were calculated as 11 σ and 10 σ for the C and Cu targets, respectively.

The ratios of the production cross section of ρ to that of ω (ρ/ω), namely, the acceptance and the decay branching ratio to the e^+e^- channel were taken into account, were also determined by the fit. Surprisingly, they are consistent with zero for both the targets, and the upper limits of the ratio at 95% C.L. are determined as 0.15 and 0.31 for C and Cu, respectively. These values are significantly less than that of the former p + p experiment, which is 1.0 $\pm$ 0.2 measured in hadronic decay channels[15].

These two kinds of anomalies—excesses on the low-mass side of the ω peak and considerably small ρ/ω ratios—can be consistently understood by assuming that the "vanished" ρ mesons have a modified shape and produce these excesses.

We have also examined the possibility that the ρ - ω interference causes a bump on the left side and the steeply falling tail on the right side of the ω-meson peak. In conclusion, there is no combination of an interference angle θ and a ρ/ω ratio that reproduces the data. All combinations within $0.2 < \rho/\omega < 3.4$ and $0.0 < \theta < \pi$ are rejected at 99.9% C.L.

4 Analysis of $\phi \to e^+e^-$ spectra

The e^+e^- spectra between 0.85 GeV/c^2 and 1.2 GeV/c^2 were fitted by the ϕ meson shape over the background curve[10]. As the ϕ meson shape, the non-relativistic Breit-Wigner formula—$d\sigma/dM \propto \frac{(\Gamma/2)^2}{(M-m_0)^2+(\Gamma/2)^2}$ —was used with a tail due to the internal radiative correction, as recently reported in Ref.[17]. The shape was filtered through the detector simulation in order to consider take the experimental effects as in the case of ρ/ω meson. The application of the relativistic Breit-Wigner formula does not change the conclusions given below. For the background shape, a quadratic curve was used instead of the mixed-event in order to absorb a possible tail from the ρ/ω region. The data were divided into three $\beta\gamma$ (= p/m) regions—$\beta\gamma$ <1.25, 1.25<$\beta\gamma$ <1.75, and 1.75<$\beta\gamma$ —for each target and fitted. All the spectra were well reproduced by the fit except for the Cu data in the slowest $\beta\gamma$ region, i.e., $\beta\gamma$ <1.25, where the fit was rejected at 99% C.L. As shown in the lower left panel of Fig. 2, the visible excess on the

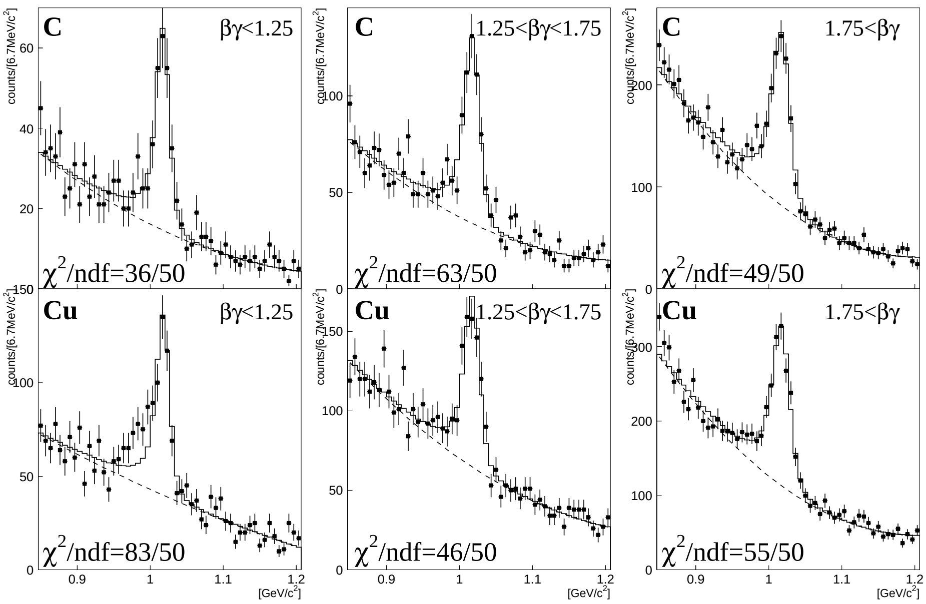

Figure 2: (preliminary) $\phi \to e^+e^-$ spectra divided into three $\beta\gamma$ regions for C and Cu targets. Only the Cu data in the slowest $\beta\gamma$ region is not reproduced well by the fit and an excess appears on the left side of the ϕ meson peak.

left side of the ϕ meson peak in the spectrum caused the failure of the fit. This is consistent with a naive picture in which the possible mass modification can be observed more easily with slowly moving mesons and larger nuclei.

5 Analysis of $\phi \to K^+K^-$ spectra

In this experiment, the $\phi \to K^+K^-$ decays were also measured[12]. The data were divided into three $\beta\gamma$ regions, namely, $\beta\gamma < 1.7$, $1.7 < \beta\gamma < 2.2$ and $2.2 < \beta\gamma$, and fitted as explained in the $\phi \to e^+e^-$ case; the only difference was that the combinatorial background, which was evaluated by the event mixing method, was used. The results are shown on the left side of Fig. 3. The data in the three $\beta\gamma$ regions for the two targets are well reproduced by the fit; in other words, no significant excess is observed. This does not contradict the $\phi \to e^+e^-$ results, which show an excess for the Cu data in $\beta\gamma < 1.25$, because the slowest region for K^+K^- is $\beta\gamma < 1.7$ and we have the statistics in the corresponding region ($\beta\gamma < 1.25$) are insufficient for achieving a fit, as shown in Fig. 3 (a). We conclude that no excesses could be observed for the ϕ meson whose $\beta\gamma$ is greater than 1.25 in both the e^+e^- and K^+K^- decay channels.

We also compared the nuclear mass-number dependence of the ϕ meson production between the e^+e^- and K^+K^- channels and found that they are statistically consistent. From this comparison, the limits for the change in the partial decay widths of the ϕ meson in nuclear matter are given in Ref. [12].

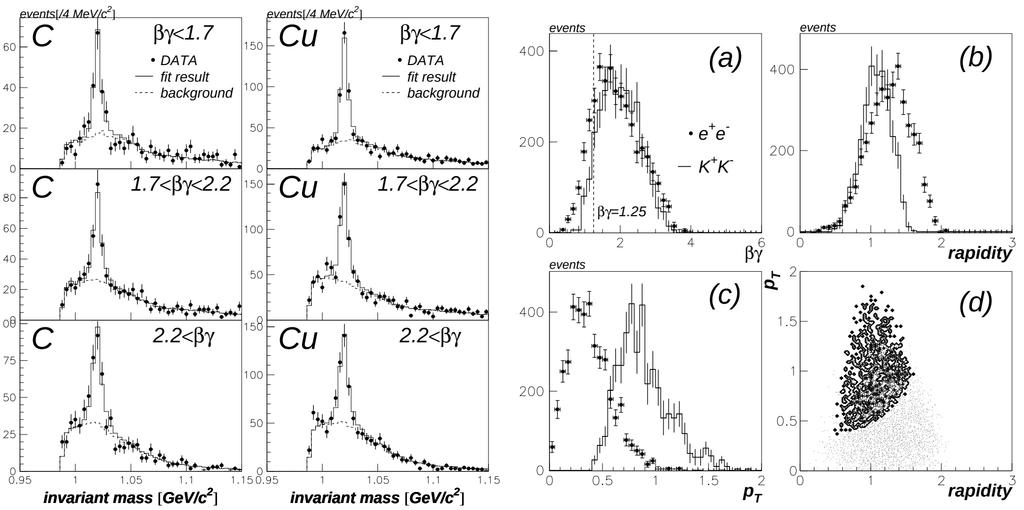

Figure 3: (preliminary) The six panels on the left show the invariant mass spectra of $\phi \to K^+K^-$ in the three $\beta\gamma$ regions for the C and Cu targets. The four panels on the right show the observed kinematical distributions of $\phi \to e^+e^-$ (solid squares) and $\phi \to K^+K^-$ (histogram) as functions of (a) $\beta\gamma$, (b) rapidity and (c) p_T. The background is subtracted by the sideband subtraction method. The spectra are the sum of the spectra of both targets. In (d), the fine dots show $\phi \to e^+e^-$ and thick contours show $\phi \to K^+K^-$ in the scatter plot of p_T and rapidity.

6 Discussion

To interpret the results that show excesses over the known hadronic sources, we introduced a simple Monte-Carlo-type toy-model in order to consider the nuclear-size and meson-lifetime dependence of the meson shapes. It should be noted that in this experiment, only a part of the mesons generated in the nuclei decay inside them and carry the information of mass modification in dense matter. Another part of the mesons that decay outside the nuclei should have a natural mass spectrum. Hence, the number of modified mesons could be larger for the slowly moving mesons, with a shorter lifetime and with a larger target nucleus.

In this model, the Woods-Saxon-type nuclear density distribution—$\rho(r)/\rho_0 \propto (1 + \exp[(r - R)/\tau])^{-1}$—is adopted, where the 'half-density' radii R of the C and Cu targets are 2.3 fm and 4.1 fm and their τ are 0.57 and 0.50 fm, respectively. The generated mesons fly through the nucleus and decay depending on their own lifetime. The hadronization time is neglected in this model. The kinematical distributions of the mesons are given by JAM, which well reproduces the observed distributions[11]. If a meson decays in a region where $\rho(r) > 0$, the pole mass is modified[1] using the formula $m(\rho)/m_0 = 1 - k_1(\rho/\rho_0)$, where m_0 is the natural pole mass of the meson and k_1 is the proportional constant, which is theoretically predicted by Hatsuda and Lee as 0.16 $\pm$ 0.06 for ρ and ω mesons[2]. In addition, width broadening of the meson is also introduced in this model using the form $\Gamma(\rho)/\Gamma_0 = 1 + k_2(\rho/\rho_0)$. This method is very simple; however, no suitable theoretical prediction that provides any analytical formula on the broadening is available for use in this case. Momentum dependences of the parameters k_1 and

[1]The prediction in Ref. [2] is not for the pole mass but for the mean value of the spectrum. These two values could be different for broad resonances.

k_2 are not considered.

It is assumed that the production points of ρ and ω mesons are uniformly distributed on the surface of the incident hemisphere at the half-density radius and ϕ mesons are uniformly produced in the entire nuclei following the nuclear density. These assumptions simply reflect the observed nuclear dependence of the production cross sections in this experiment. The cross sections are parametrized as $\sigma(A) \propto A^{\alpha}$, and the value of observed α is $\sim$2/3 for ω and $\sim$1 for ϕ (see footnote[2]).

Finally, the filtering by the detector simulation is performed against decayed e^+e^- . By using the obtained meson shapes including modification as described above, the spectra were fitted after subtracting the background and η/ω Dalitz decays. We attempted to determine the best fit by changing the modification parameter k_1 and the ρ/ω ratio. A common value of k_1 was applied to ρ and ω and to C and Cu. The best fit value of k_1 is 0.092 ± 0.002, whereas the best fit values of the ρ/ω ratio are 0.7 ± 0.1 and 0.9 ± 0.2 for the C and Cu targets, respectively[9]. The obtained k_1 value means a mass reduction of approximately 9% at the normal nuclear density ρ_0. It is interesting that the ρ/ω ratios become consistent with the former experimental value of 1.0 ± 0.2[15]. The model analysis reveals that the width broadening of ρ and ω is not preferable. In fact, the broadening of ρ and ω mesons contradicts the data due to the right-hand side tail of the ω meson peak, which falls very steeply.

In the ϕ meson case[10], the amount of excess observed in the slowest $\beta\gamma$ region for the Cu target data cannot be explained only by the pole-mass shift. We must extend the decay probability to the e^+e^- channel. By assuming that Γ_ϕ is broadened and $\Gamma_{e^+e^-}/\Gamma_\phi$ is unchanged, a simultaneous fit for the three $\beta\gamma$ regions for both of the C and Cu data was performed using modified shapes with common values of k_1 and k_2 to C and Cu. The preliminary best fit value of k_1 is $0.035^{+0.005}_{-0.008}$ and that of k_2 is $2.6^{+1.8}_{-1.2}$, which shows that 3.5% decrease in the pole mass and a factor of 3.6 of Γ_ϕ broadening at ρ_0.

7 Conclusion

Invariant mass spectra of the e^+e^- channel were measured with the world highest mass resolution of 10.7 MeV/c^2 for the ϕ meson . Approximately 2000 $\phi \to e^+e^-$ decays were accumulated in each of the 12 GeV p + C and p + Cu reactions. A significant excess over the known hadronic sources was found on the low-mass side of the ω meson peak for both targets. These excesses cannot be explained by the ρ - ω interference nor by various ρ meson shapes, as described in Appendix B. The model analysis showed that the modification of ρ and ω mesons in cold nuclear matter can explain both the excesses and the disappearance of ρ mesons in the natural shape. Furthermore, we observed a significant excess on the left side of the ϕ meson peak when ϕ mesons moved slower in a larger nucleus. This is the first observation of the ϕ meson spectral modification in nuclear matter. This discovery is only possible with the present mass resolution and statistics. The $\phi \to K^+K^-$ measurements are consistent with the $\phi \to e^+e^-$ results.

[2] $\alpha = 0.710 \pm 0.021$(stat.) ± 0.037(syst.) for ω and 0.937 ± 0.049(stat.) ± 0.018(syst.) for ϕ in the e^+e^- channel [11].

Acknowledgments

We would like to thank all the staff members of the KEK–PS, particularly the beam channel group for their helpful support. This study was partly funded by the Japan Society for the Promotion of Science, RIKEN Special Postdoctoral Researchers Program, and a Grant-in-Aid for Scientific Research from the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT). Finally, we thank the staff members of the RIKEN super combined cluster system (RSCC) and RIKEN–CCJ.

A Event mixing method

The event mixing method is used to evaluate the shape of the combinatorial background. Since the multiplicity is lower and the signal to background (S/B) ratio is higher than that in usual heavy ion experiments, we must use a technique that differs slightly from the one used in such experiments.

In this experiment, the track multiplicity for electrons and positrons in a triggered event is approximately two and almost all events have only one electron and one positron. Therefore, for the normalization of the mixed event, we cannot use the formula $N_{+-} = 2\sqrt{N_{++}N_{--}}$, which is based on the assumption that the number of tracks with each charge follows the binomial distribution[18]. Hence, we determined the normalization by the fit.

Moreover, the S/B ratio for the ω resonance is approximately 3:1 at the peak bin. This implies that the electron (positron) track from the resonance could distort the shape of the mixed events. In order to avoid any possible distortion, a simple solution is not to use the resonance region such as ω in the event mixing. In the present analyses, we adopted the "weighting method" described later instead of the simple solution. Further, we treated the deviation from the results obtained by the simple solution as a systematic error of the background determination. In the weighting method, we used all the electrons and positrons in the mixing events with weights as a function of mass. The weights were iteratively determined such that the observed spectrum multiplied by the weights coincided with the background shape.

B ρ resonance shape

We used the following relativistic Breit-Wigner formula for the broad resonances:

$$\frac{d\sigma}{dM} \propto \frac{M^2\Gamma_{tot}(M)\Gamma_{ee}(M)}{(M^2 - m_0^2)^2 + m_0^2\Gamma_{tot}(M)^2} \tag{1}$$

By using in the running widths $\Gamma_{tot}(M) = \frac{M}{m_0}\Gamma_{tot}$ and $\Gamma_{ee}(M) = \frac{m_0^3}{M^3}\Gamma_{ee}$, we obtained (2):

$$\frac{d\sigma}{dM} \propto \frac{m_0^2\Gamma_{tot}\Gamma_{ee}}{(M^2 - m_0^2)^2 + M^2\Gamma_{tot}^2} \tag{2}$$

which is the same as that used by CERES[3];

$$\frac{d\sigma}{dM} \propto \frac{(1 - 4m_\pi^2/M^2)^{3/2}}{(M^2 - m_0^2)^2 + M^2\Gamma_{tot}^2}(2\pi MT)^{3/2}e^{-M/T} \tag{3}$$

except for the Boltzmann factor $(2\pi MT)^{3/2}e^{-M/T}$ and the factor $(1-4m_\pi^2/M^2)^{3/2}$, which arises that that the initial channel is dominated by $\pi^+\pi^- \to \rho$.

When we analyzed the data using (2), the stability of the statistical significance of the excesses was examined by changing the fit region and by changing the shape of the ρ meson to the Gounaris-Sakurai shape[19], CERES-type RBW formula (3) and even to the non-relativistic BW formula. Throughout these trials, the significance of the excesses were maintained at 9∼11 σ for C and 9∼10 σ for Cu.

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